Lecture #10

From Chapter 3 in Jaeger, Chapter 2 in Spencer

Diodes Basics

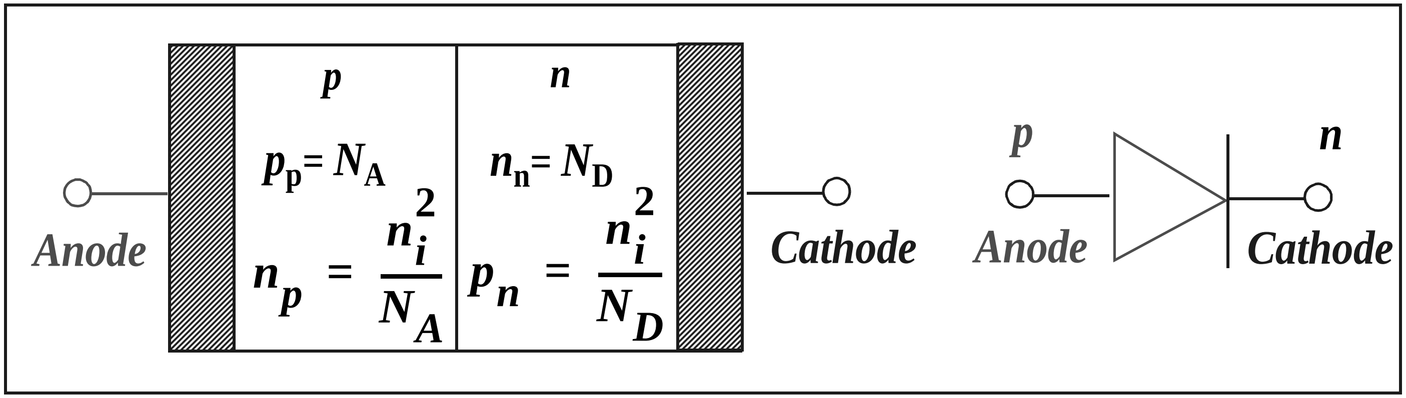
Outline/Learning Objectives:

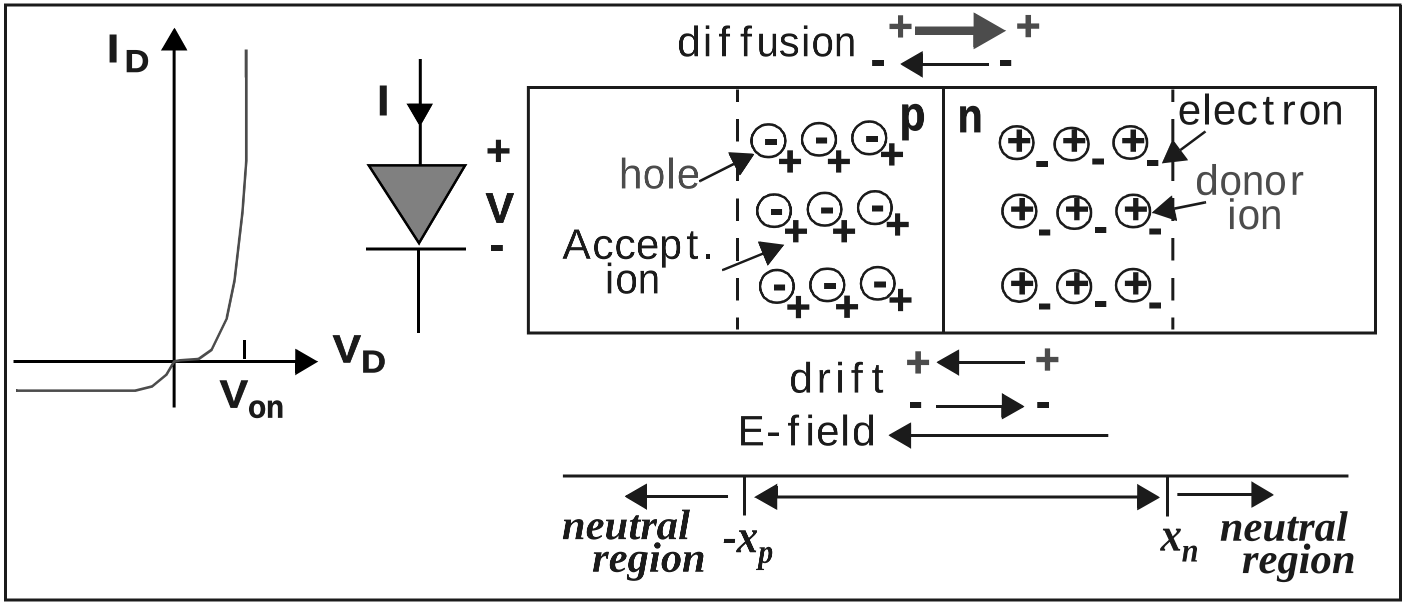
- pn junction electrostatics
- Mathematical model of the pn junction
- pn junction capacitance

Selected Problems

3.31, 3.70, 3.71, 3.78, 3.127, 3.129

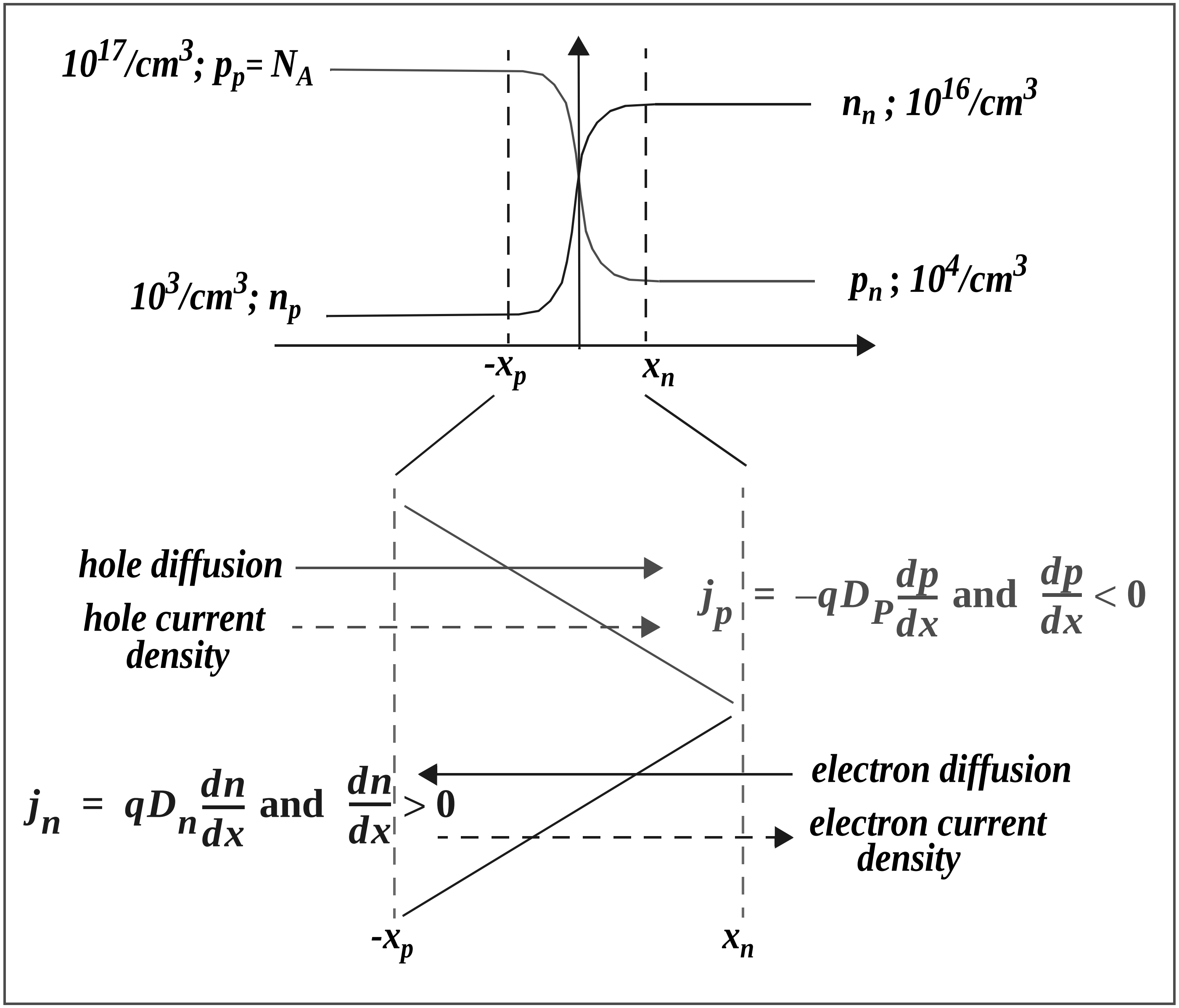
How the Diode Works





Explain space charge region (SCR) near to metallurgical junction which is depleted of mobile carriers (depletion layer or depletion region).

pn junction electrostatics

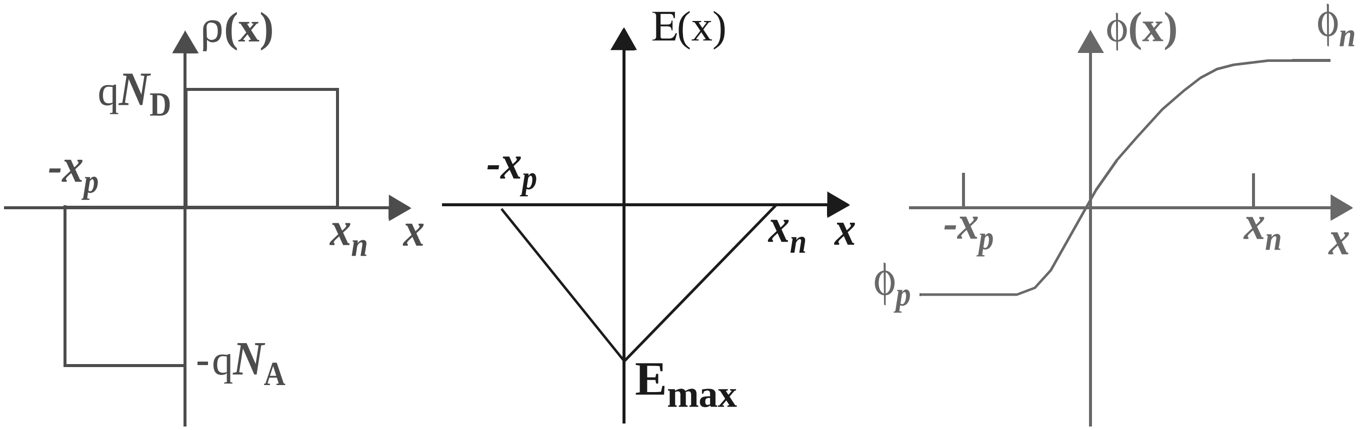


$$j_p = -qD_P\frac{dp}{dx} \text{ and } \frac{dp}{dx} < 0$$

$$j_n = qD_n\frac{dn}{dx} \text{ and } \frac{dn}{dx} > 0$$

Gauss' Law - $\boxed{\nabla \cdot E = \frac{\rho_c}{\varepsilon_s}}$, so in 1D, we get $\boxed{E(x) = \frac{1}{\varepsilon_s}\int \rho(x)dx}$.

Total depletion layer width is $\boxed{w_{do} = x_n + x_p = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\phi_J}}$.



$$qN_A x_p = qN_D x_n$$

$$\phi_J = -\int_{x_n}^{x_p} E(x')dx' = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Majority carriers - holes in p-region and electrons in n-region.

Holes diffuse from p to n and recombine with many of the free electrons there in **n-type** material. Leaves uncovered bound negative charges in L of junction (acceptor ions).

Electrons diffuse from n to p and recombine with many of the free holes there in **p-type** material. Leaves uncovered bound positive charges in R of junction (donor ions).

Diffusion of majority carriers leaves uncovered bound charges in space charge region (SCR) and creates an internal electric field from R to L.

Under E-field, minority carriers drift across the junction.

$$\boxed{E = \frac{1}{\varepsilon_{Si}}\int \rho dx \text{ since } E = -\frac{dV}{dx}}.$$

Potential barrier or height act to oppose diffusion of majority carriers - h (L --> R) and e (R --> L) and encourage drift of minority carriers.

Under OC conditions, net current is zero. Tendency of majority carriers to diffuse is just balanced by minority carriers to drift across junction.

Example

$$N_A = 10^{18} cm^{-3}\ ;\ N_D = 10^{14} cm^{-3}\ ;\ n_i = 10^{10} cm^{-3}\ ;$$

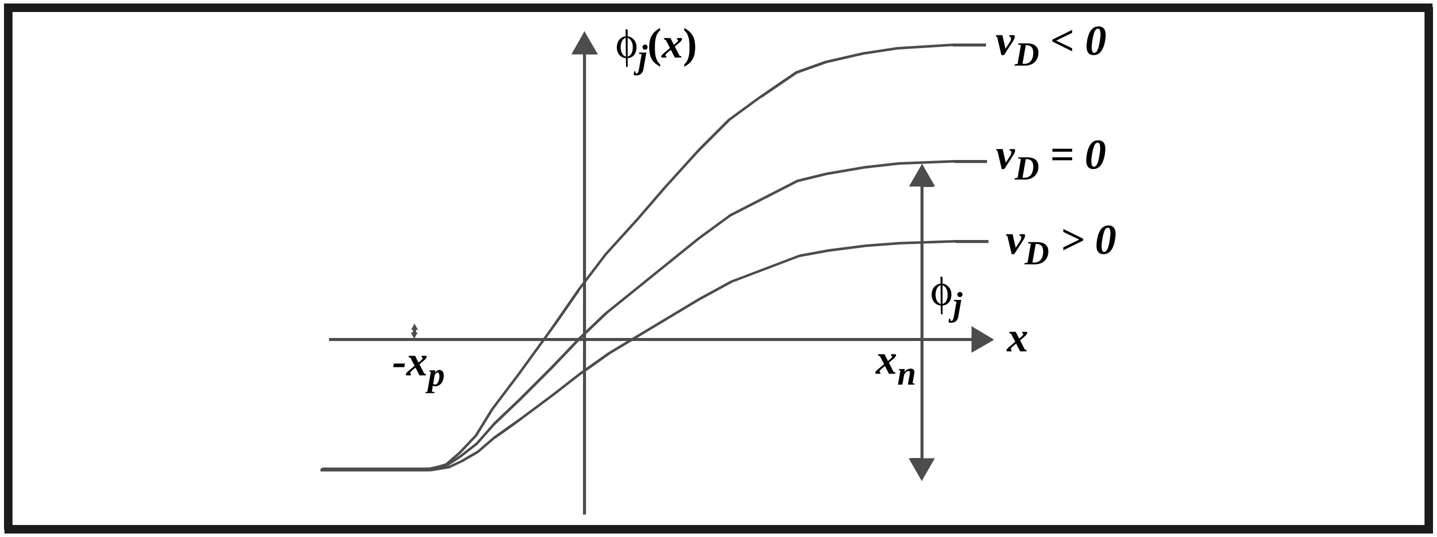
$$\mathrm{T = 300K};\ \varepsilon_s = 11.7 \times 8.854 \times 10^{-14} \frac{F}{cm};\ \phi_J = 0.7V;\ V_T = 0.0258V.$$

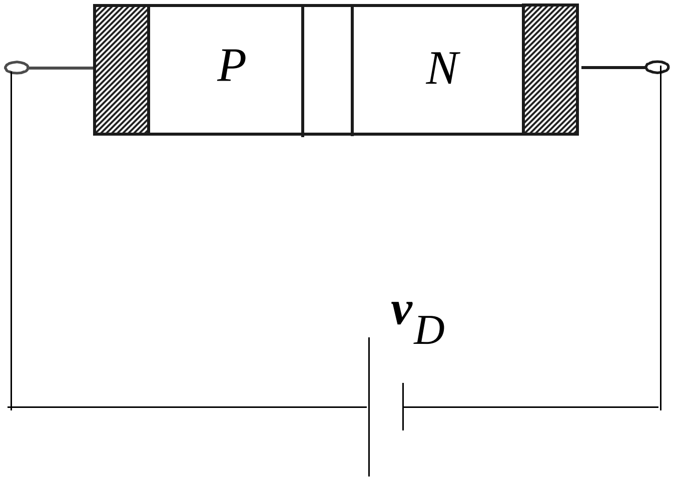
$$\boxed{x_n = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\phi_J} \cdot \frac{N_A}{N_A + N_D} = 3.03\mu m}$$

$$\boxed{x_p = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\phi_J} \cdot \frac{N_D}{N_A + N_D} = 3.03 \times 10^{-4}\mu m}$$

$\boxed{j_n^T = \left(qn\mu_n E + qD_n\frac{\partial n}{\partial x}\right)}$ and $\boxed{j_p^T = qp\mu_p E - qD_p\frac{\partial p}{\partial x}}$ in A/cm^2.

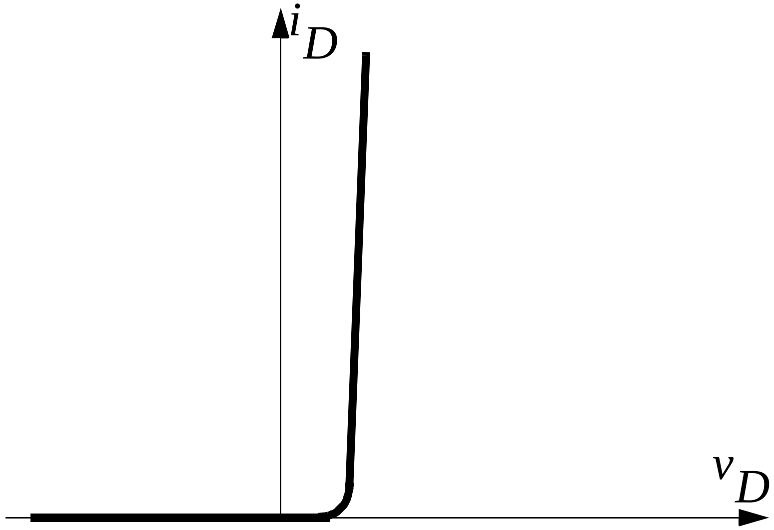
The Diode behavior under applied voltage





Mathematical Model of the Diode

$$i_D = I_s \cdot \left(e^{qv_D/nkT} - 1\right)$$



Reverse saturation current (I_s)

is independent of the junction potential.

I_s doubles for every 10^o increase

in temperature, near room temperature.

n - ideality factor (1 to 2) q - electron charge $(1.6x10^{-19}C)$

v_D - diode voltage k - Boltzmann constant $\left(1.38x10^{-23}\frac{J}{K}\right)$

Reverse biases: $\boxed{i_D \approx -I_s \quad \text{for} \quad v_D \ll \frac{nkT}{q} = nV_T}$. Zero V: $\boxed{i_D = 0}$.

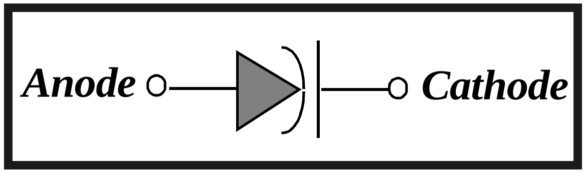
Forward biases: $\boxed{i_D = I_s \cdot e^{qv_D/nkT} \quad \text{for} \quad v_D \gg nV_T}$. (usually $4V_T \approx 0.1V$)

PN Junction Capacitance

Reverse Bias $Q_n = qN_D x_n A = q\left(\frac{N_A N_D}{N_A + N_D}\right) w_d A$

$$\boxed{w_d = x_n + x_p = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(\phi_J + v_R)}}$$

$$C_J = \frac{dQ_n}{dv_R} = \left(\frac{\varepsilon_{Si} A}{w_{d0}}\right)\frac{1}{\sqrt{1 + v_R/\phi_J}}$$

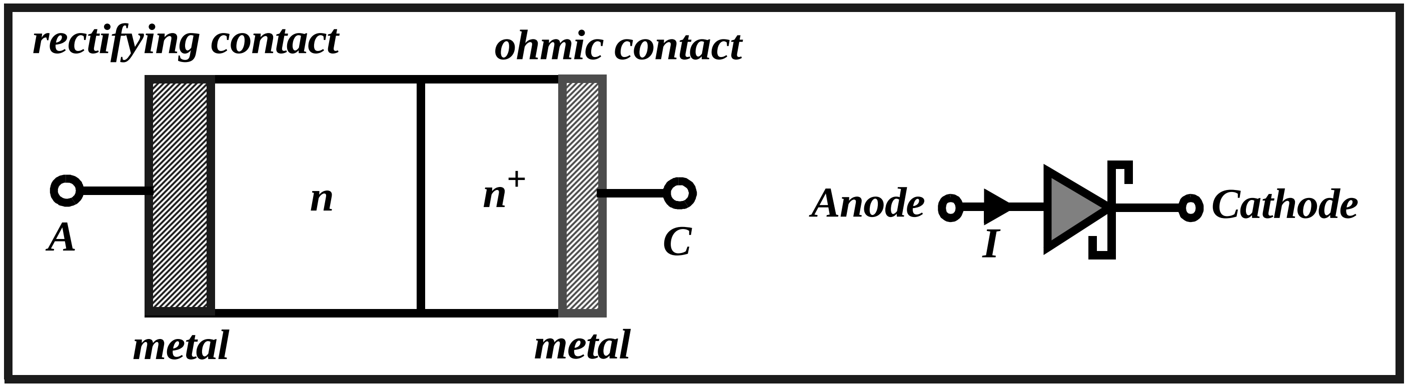


Can be a V-controlled Capacitor (varactor)

Forward Bias $Q_D = i_D \tau_T$ where τ_T is the diode's transit time (1 fs to > 1 μs - depends on type and size of diode).

Diffusion capacitance $\boxed{C_D = \frac{dQ_D}{dv_D} = \frac{i_D \tau_T}{V_T}}$.

Schottky Barrier Diode



Characteristics - lower V_{on}.

- significantly reduced charge at v_F.
- used in bipolar logic circuits.